Fuel of Novel Generation for PWR and as Alternative to MOX Fuel

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Improving fuels for PWR and WWER reactors:

- increasing the U content of the fuel meat,
- lowing down the temperature in the fuel,
- extending of the burnup,
- serviceability under transients

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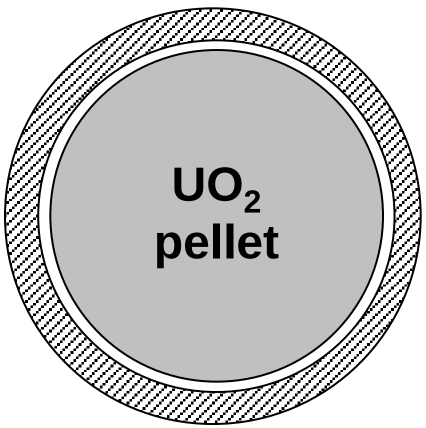
Novel approach to Fuel Development

To replace the container design fuel rod with UO_2 pellet to METMET fuel (U-Mo, U-Zr-Nb, U_3Si) with Zr alloy matrix



Uranium density

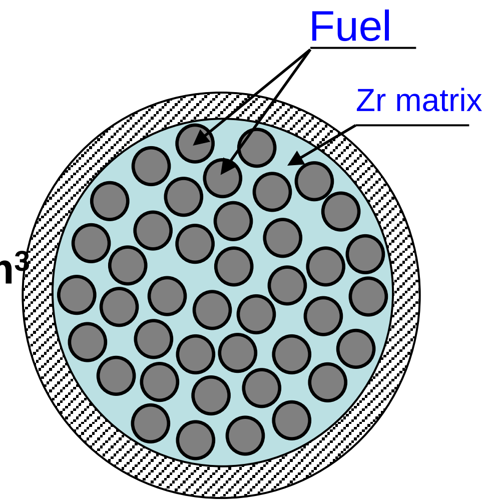
8.3-8.5 g/cm^3 *(10.5 in pellets)* **>10 g/cm^3**

Serviceability in transients

Low **High**

Fuel temperature

1600^0C **450^0C**



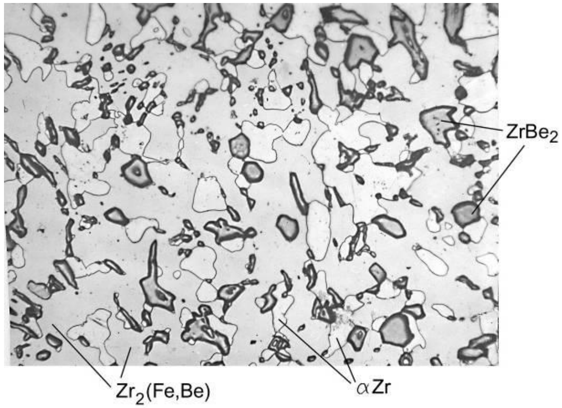
Peculiarities of Dispersion Type Fuel

- **High irradiation resistance and high burn-ups,**
- **High thermal conductivity (cold fuel),**
- **Metallurgical bond between fuel and cladding promotes serviceability in transients**

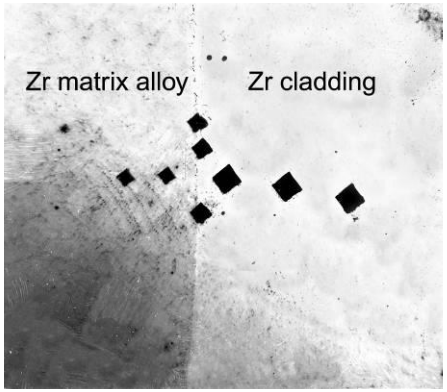
Properties of Zr matrix alloys

№ of group	Contents of alloying elements, % mass				Melting Temperature ℃	Compression Strength at 500℃, MPa	Thermal Conductivity at 500 ℃, $Wm^{-1}K^{-1}$
	Zr	Fe	Cu	Be			
1	base	4-8	0.1-3.0	2-3	780-810	500	21-25
2	base	6-12	6-12	-	850-860	530	22-26

Ingots, from Zr matrix alloys



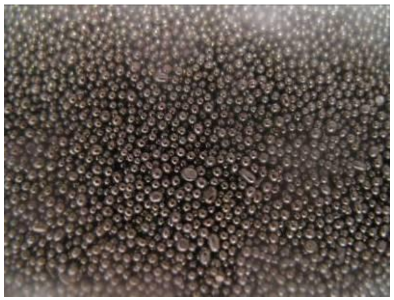
Microstructure of Zr alloy



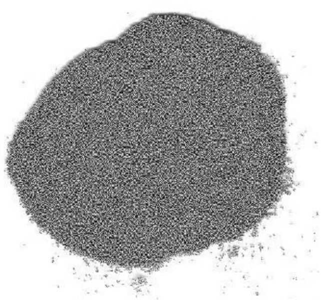
Bonding with Zr cladding

Fuel element fabrication technology

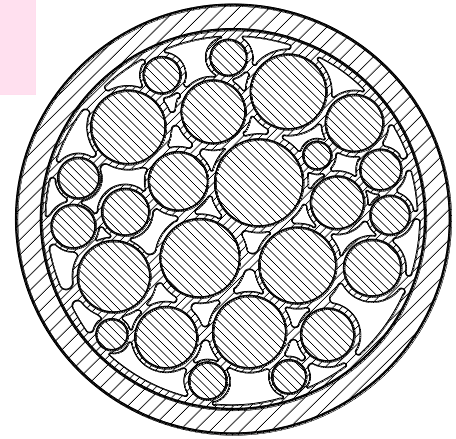
Under annealing (850^{0}C – 1 minute) matrix granules melts down and under capillary forces moves into gaps between the fuel components to form metallurgical bonds

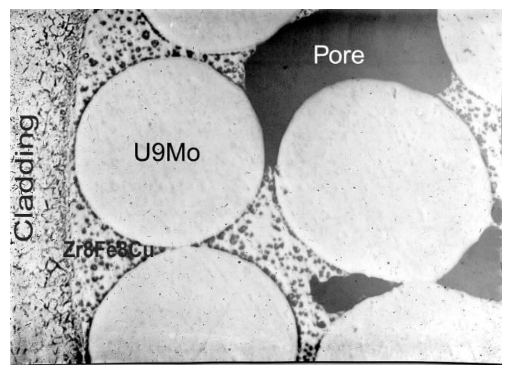


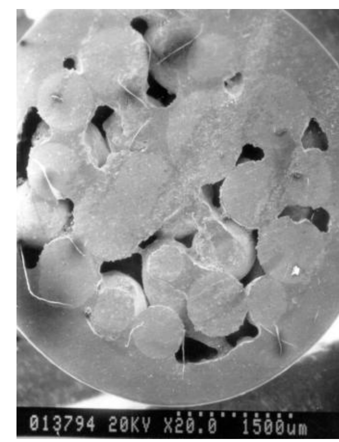
UMo, U-Zr-Nb, U_3Si granules



Zr matrix alloy, granules







<u>The fuel</u>	**up to 66%**
The matrix	**15-20%**
The pores	**16-20%**

Micro and macro structure of fuel composition

Properties of fuel compositions

For PWR and especially CANDU (HWPR) reactors are very promising to further increase the fuel meat uranium content via increasing the volume fraction of fuel granules. Following this method we have reached 72% volume fraction of fuel at 14% of matrix and 14% of pores

Micro and macrostructure of modified fuel composition with higher uranium content (72% volume fraction of fuel under the cladding)

Properties of fuel compositions

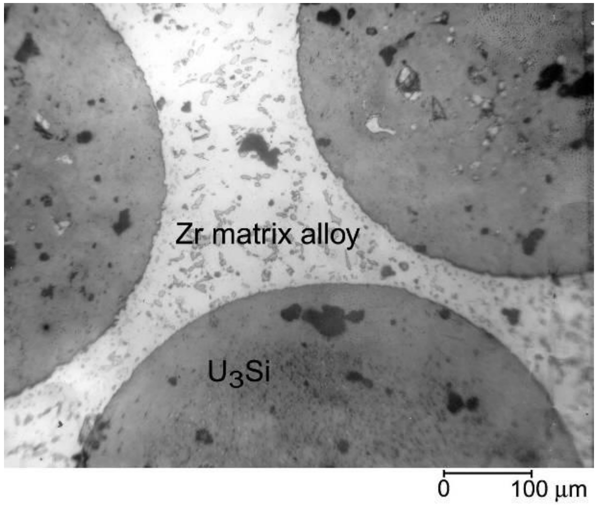
Fuel		U_3Si	U-9Mo	U-1.5Mo-1.0Zr	U-5Nb-5Zr	U-3Nb-1.5Zr	UO_2 pellet
U content in fuel composition at volume fraction of fuel	66 %	9.6	10.7	11.9	9.8	11.34	8.4-8.5
	72 %	10.45	11.7	12.9	10.7	12.37	
Increase of U content, %		13-24	26-38	42-55	15-26	35-47	0
Thermal conductivity at 500 °C, $W \cdot m^{-1} \cdot K^{-1}$		19	22	24	18	21	2-4
Interaction layer after annealing at 750 °C for 6000h, μm		7-10	10-15		15-25		
Corrosion rate in water at 330^0C (g/m^2h)		0.03	0.05		0.02		

Since the volume fraction of the fuel is up to 66-72 %, with the use of high uranium content fuel the uranium content attains 9.5-12.5 g/cm^3.

Aqueous corrosion rate of dispersion fuel at 350 °C is 0.02-0.04 g·m-2·h-1.

Properties of fuel compositions

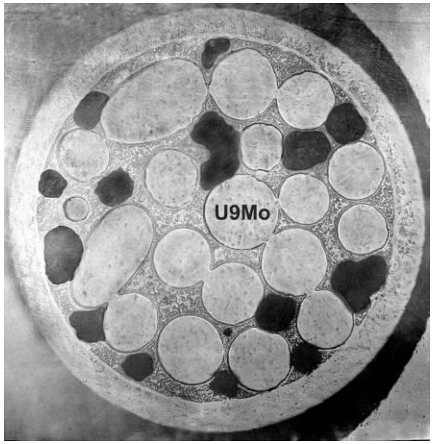
Compatibility

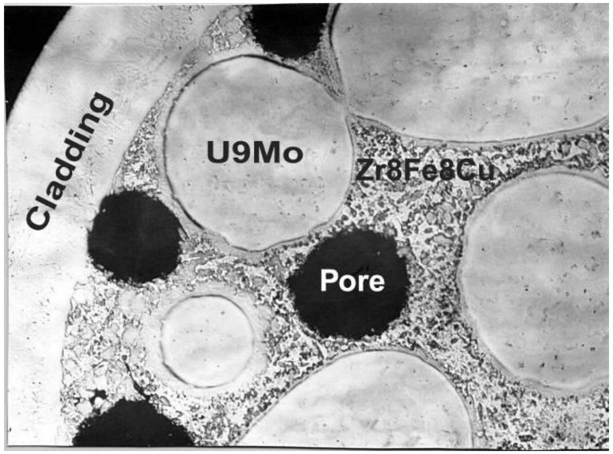


U_3Si + Zr-6.3Fe-2.4Be
750 °C - 6000 h

Accident conditions

U9Mo + Zr8Fe8Cu (1000^{0}C – 30 min)





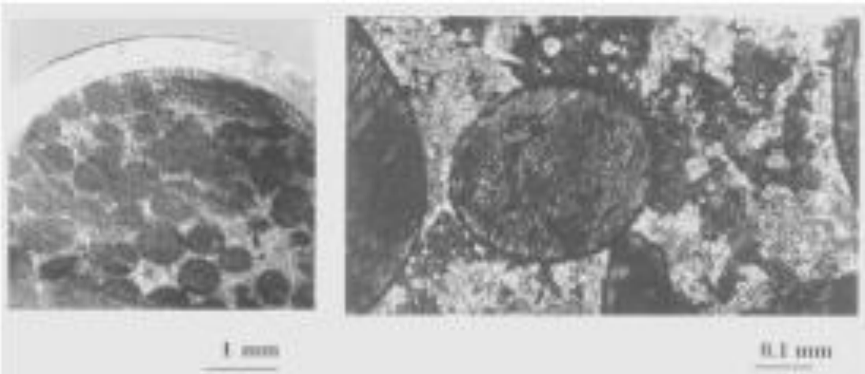
After fuel element fabrication the melting temperature of the Zr matrix alloys increases

Since zirconium forms the base of the matrix it is compatible with the high uranium content fuel both upon fabricating fuel elements and after long-term isothermal anneals of fuel compositions at 750 °C for 6000 hours

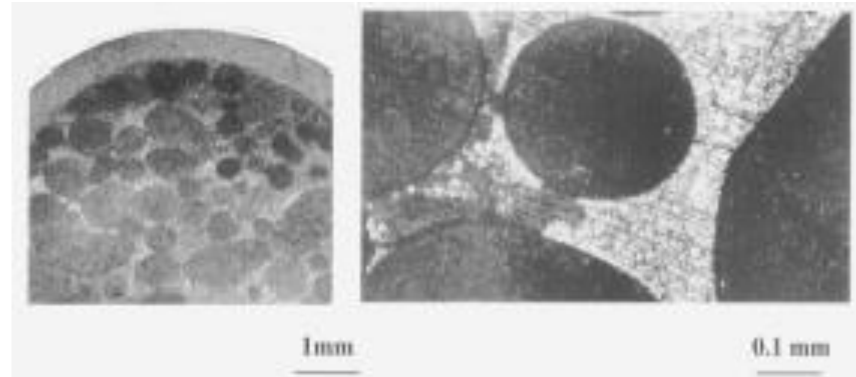
For cold fuel the accident scenario is less severe (instead of 1100^{0}C for pelletized UO_2 fuel it will be only 700-800^{0}C for METMET fuel).

Properties of fuel compositions

In-pile tests *(Structures of irradiated fuels)*



U5Nb5Zr (burn-up of 0.5 g-fiss/cm^3)



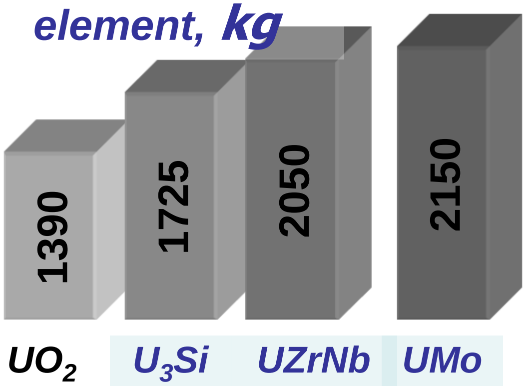
U_3Si (burn-up of 0.4 g-fiss/cm^3)

Fuel	Clad / fuel temperature, ^{0}C	Fuel element type	Burn-up	
			g-fiss/cm^3	MW*d/kgU
UO_2 + Zr alloy U5Nb5Zr + Zr alloy U_3Si + Zr alloy	300/500 300/450 300/450	Fuel compositions	0.8 0.5 0.4	100 67 53
UO_2 + Zr alloy	330/500	RBMK	0.4	55
UO_2 + Zr alloy	330/440	WWER-440	0.45	60
UO_2 + Zr alloy	600/750	Special	1.5	200

Advantages **for use in PWR and WWER**

1. **High uranium content up to 12.5 g/cm³ under the cladding - the uranium enrichment to be reduced or the burnup to be increase.**

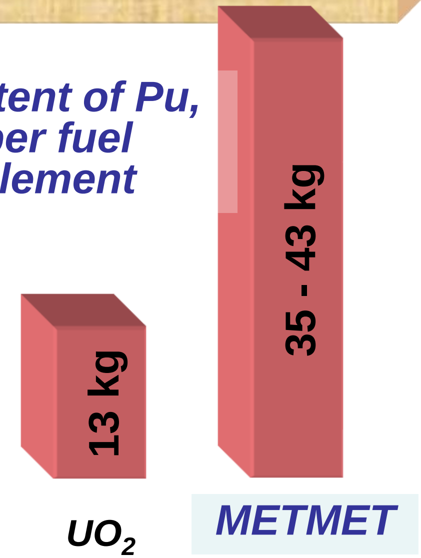
*U content in a VVER-1000 fuel element, **kg***



Additionally 450-500 effective days or 3.0% enrichment instead of 4.95%

Prolongation the Company more than 30%

Content of Pu, per fuel element



2. Cold fuel – the fuel temperature 400-500 °C .

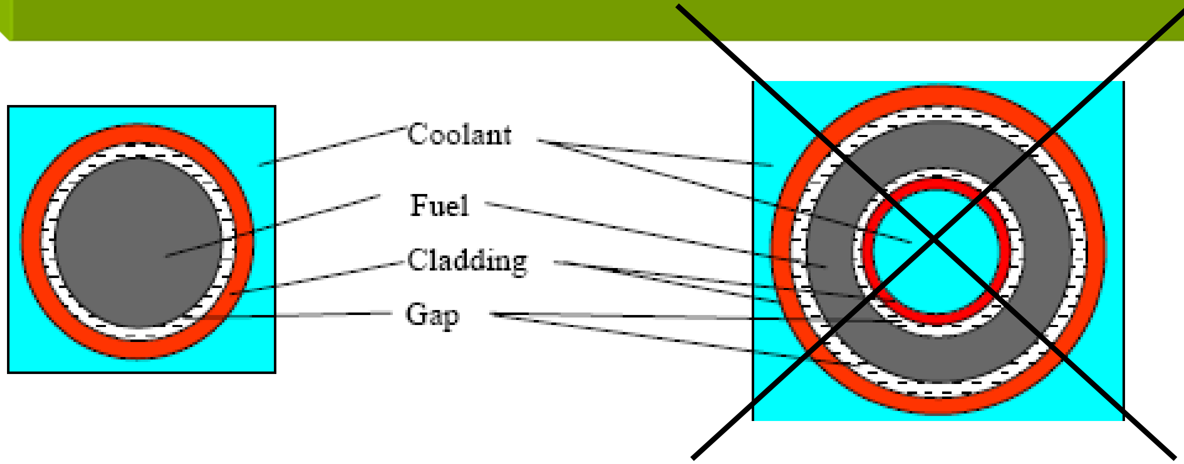
3. **Accommodation of swelling and anticipated the burnup up to 1.0 g.fiss/cm³ (120 MW*d/kgU.) - Prolongation fuel company.**

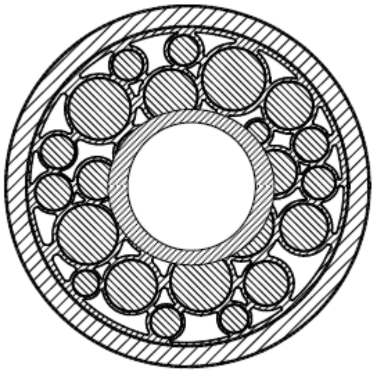
4. Serviceability under transients due to metallurgical bond between the fuel and the cladding that leads to optimization of Nuclear Plant operation conditions and improvements of their operation reliability and safety.

5. High resistance to aqueous corrosion at high parameters.

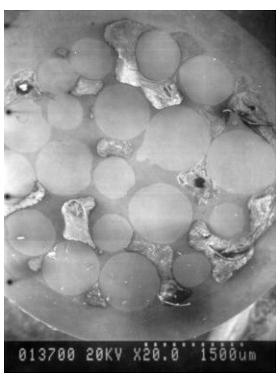
Advancing Fuel Development

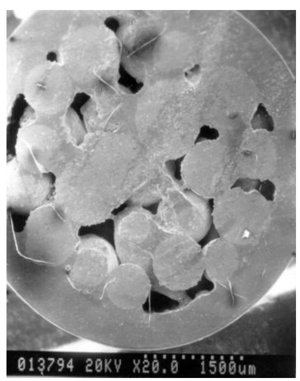
Annular or smaller outer diameter fuel with high power density



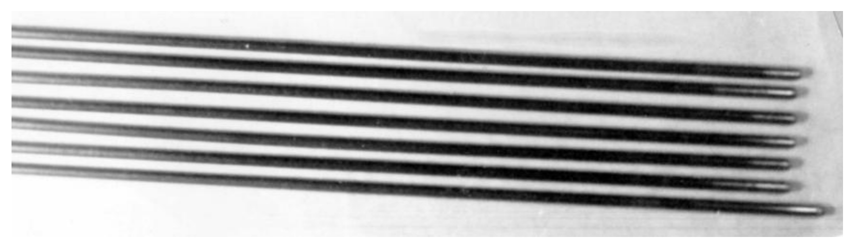


Possibility of large Power upgrades (up to 30-50%)





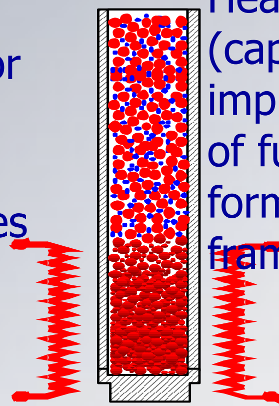
Macrostructures of fuel rods for Floating Power Plant (6.8 mm diameter)



Annular dispersion type fuel can permits VVER-1000 reactor produce energy power as VVER-1500 reactor.

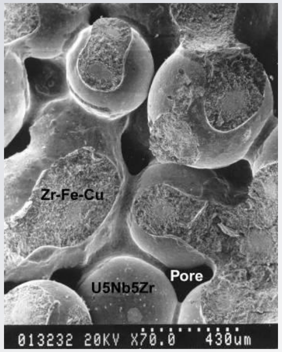
Closing Fuel Cycle - Combined U(Th)-PuO_2 Fuel instead of MOX

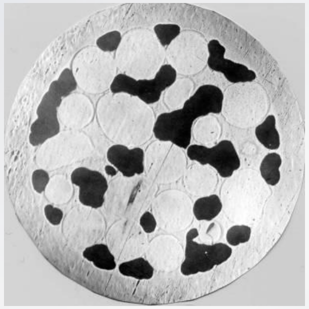
Loading of mixed U^{238} or Th fuel and Zr matrix alloy granules



Heating (capillary impregnation of fuel to form U(Th) frame

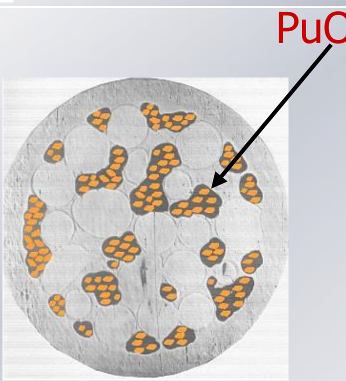
Final stage of U^{238} – PuO_2 fuel element fabrication - PuO_2 loading into blank fuel element

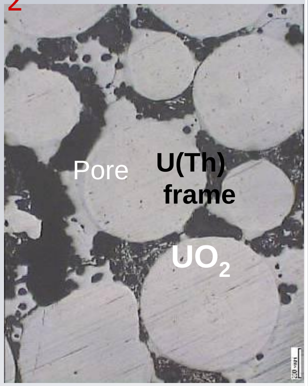




Blank fuel element

Final fuel element

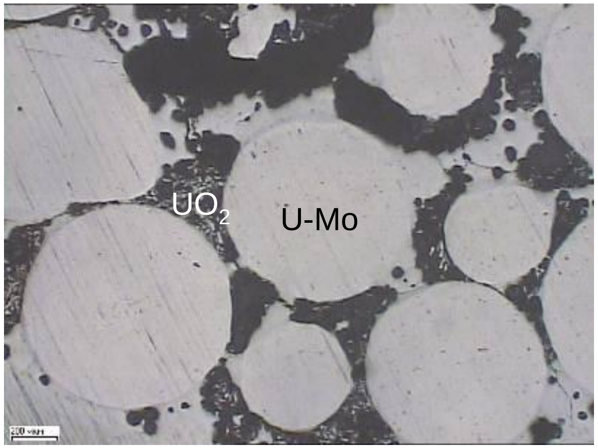




High porosity U(Th) frame prior to vibrofilling with PuO_2 powder

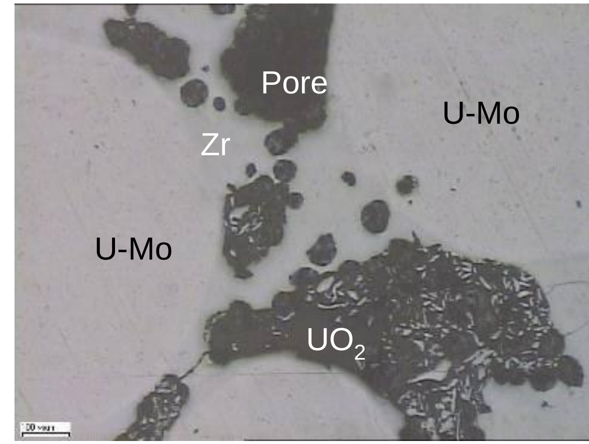
Environment-friendly fabrication process, high uranium density, low fuel temperature, workability in transients, high burn-up, closing fuel cycle

Closing Fuel Cycle - Combined U(Th)-PuO2 Fuel instead of MOX



Microstructure of combined fuel (UO_2 is used in place of PuO_2)

In this option granules of Zr matrix and UO_2 were loaded simultaneously into fuel element cladding before annealing.



The advantages of this fuel element as an alternative to the MOX one are:

1. The process of the fuel element fabrication is environmentally more friendly.

2. The higher uranium content of a fuel element, hence, the higher conversion ratio.

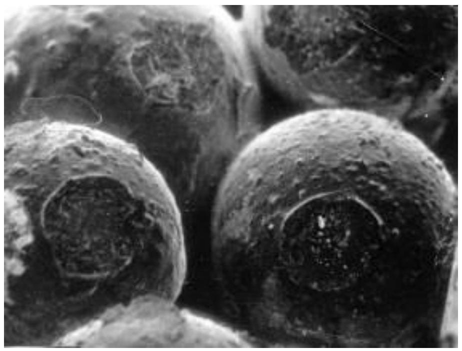
3. Low temperature of fuel (cold fuel).

4. Serviceability under transient conditions

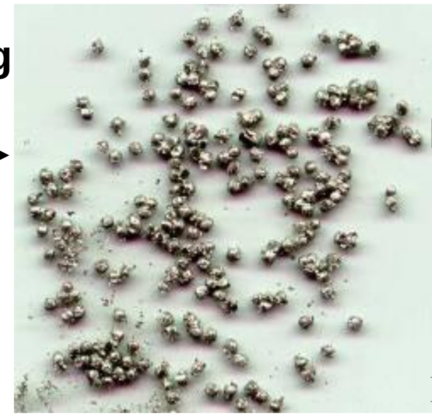
REPROCESSING OF NOVEL METMET FUEL

Reprocessing without chemical processes with repeated use in RBMK, CANDU

U(Th) alloy
+Zr matrix
+(PuO_2)



Grinding



<u>Coarse fraction</u>
with generated Pu (3-4%)or U^{233}:
U(Pu)-Mo,
U(Pu)-Zr-Nb,
(U,Pu)Si_3 alloys

Repeated use in RBMK, CANDU

<u>Fine fractions</u>:
1. Zr matrix;
2. Burnt PuO_2 in case of combined fuel

Via heating gas fission products are removed from fuel (DUPIC like process)

Separation fissile atoms (Pu^{239},Pu^{241}) from unfissile one (Pu^{240}, Pu^{242})

Reprocessing process more workable and environmentally friendly, which simplifies the closing of the nuclear fuel cycle

Conclusion

- To accomplish a further qualitative ramp in novel generation fuel development we suggest to replace the container design fuel rod, the possibilities of which is practically exhausted, to dispersion type fuel elements
- Advantages of novel principle:
- - Achievement of super extended burn-ups (up to 120 MW*d/kgU): introduction of cost-effective fuel cycles, reduced consumption of natural uranium and lower amounts of spent nuclear fuel.
- - Application of high density metal fuel, which reduces uranium-235 enrichment, increases conversion ratio, ensures inherent safety of reactor plants and improves the economics of nuclear power.
- - Putting in practice 'cold' nuclear fuel concept.
- - Serviceability under transients, which optimizes cost-effective conditions of Nuclear Power Plant operation.
- - Replacement of MOX fuel by mastered in Russia alternative plutonium and uranium containing fuel.

As a result – the increase of economic efficiency and lower cost of electrical power to be supplied to customer

Thank you
for your attention!